QUANTUM APPROACHES TO CONSCIOUSNESS.

1. Introduction.

Quantum approaches to consciousness are sometimes said to be motivated simply by the idea that quantum theory is a mystery and consciousness is a mystery, so perhaps the two are related. That opinion betrays a profound misunderstanding of the nature of quantum mechanics, which consists, above all, in a pragmatic scientific solution to the problem of the relationship between mind and matter. A key achievement of the founders of quantum theory was to forge a rationally coherent and practically useful linkage between the two kinds of descriptions that jointly comprise the foundation of science. Descriptions of the first kind are of psychologically experienced empirical findings, expressed in a language that allows us to communicate to our colleagues what we have done and what we have learned. They are descriptions of how we have acted, and what kinds of experiential responses have followed from these actions. Descriptions of the second kind are descriptions of physical states, expressed in terms of mathematical properties assigned to space-time points. A new conception of the linkage between these two kinds of description was formulated by Bohr, Heisenberg, Pauli, and their colleagues, and this conception was subsequently extended by John von Neumann from the domain of atomic science to the realm of neuroscience and, in particular, to the problem of the relationship between the minds and brains of human beings.

This new understanding of the relationship between the psychologically and physically described components of scientific practice was achieved by abandoning the classical conception of the physical world that had ruled science since the time of Newton, Galileo, and Descartes. The building blocks of science were enlarged from descriptions of tiny bits of mindless matter, and of the interactions between them, to include descriptions of both *the actions that we take to acquire knowledge*, and of the knowledge that we thereby acquire. Science was transformed from its seventeenth century form, which effectively excluded our conscious thoughts from any fundamental role in the dynamical workings of nature, to its twentieth century form, which, at least at the practical or pragmatic level, injects our conscious choices of the actions we perform into the basic dynamical structure of physical theory.

The twentieth century brought a clearer recognition of the fact that *science is a human activity* that involves not just our passive witnessing of the deliverances of a mechanistically controlled physical world, but also our choices about how we probe nature. The laws of nature, as they are now understood through quantum mechanics, not only forbid us from rationally asserting that these conscious choices are themselves fixed by mechanical processes, but, moreover, exploit the *effective freedom of choice* by introducing these *empirically accessible and experimentally controllable conscious choices about how to act* into the dynamical theory as dynamically efficacious input parameters, replacing classical microscopic concepts that are *empirically inaccessible as a matter of principle.*

This new understanding underlies the following pronouncements of Heisenberg and of Bohr:

“The conception of the objective reality of the elementary particles has thus evaporated not into the cloud of some obscure new reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the particle but rather our knowledge of this behavior.” (Heisenberg, 1958)

“In the great drama of existence we ourselves are both actors and spectators.” (Bohr, 1963: 15, 1958: 81)

Wheeler calls the observers “participants” to emphasize this essentially *active role of conscious agents* in quantum dynamics.

Comprehending this new conception of the relationship between the psychologically experienced empirical side and the mathematically described physical side of the scientific endeavor requires an appreciation of a certain novelty in the logical structure of quantum theory, but this fundamental conceptual shift can be comprehended without becoming enmeshed in technical mathematical details.

The Classical-Physics Approach.

To grasp the essential change one must know what came before.

Classical physics arose from the theoretical effort of Isaac Newton to account for the findings of Johannes Kepler and Galileo Galilei. Kepler discovered that the planets move in orbits that depend on the location of other physical objects - such as the sun - but not on the manner or the timings of our observations: minute-by-minute viewings have no more influence on a planetary orbit than daily, monthly, or annual observations. The nature and timings of our observational acts have no effect at all on the orbital motions described by Kepler. Galileo observed that certain falling terrestrial objects have similar properties. Then Newton discovered that he could explain *simultaneously* the celestial findings of Kepler and the terrestrial findings of Galileo, and others, by postulating that all objects in our solar system are composed of tiny planet-like particles whose motions are controlled by *laws* that refer to the relative locations of the various particles, but that make no reference to any conscious acts of experiencing, which are taken to be simply direct passive witnessings of certain macroscopic properties of large conglomerations of the tiny invisible particles.

Newton's laws involve instantaneous action at a distance: each particle has an instantaneous effect on the motion of every other particle, no matter how far away it is. Newton considered this non-local feature of his theory to be unsatisfactory, but proposed no alternative. Eventually, Albert Einstein, building on ideas of James Clerk Maxwell, constructed a *local* classical theory in which all dynamical effects are generated by contact interactions between mathematical described properties localized at space-time points, and in which no effect is transmitted faster than the speed of light.

All classical-physics models of nature are *deterministic*: the state of any isolated system at any time is completely fixed by the state of that system at any earlier time. The Einstein-Maxwell theory is deterministic in this sense, and also "local", in the just-mentioned sense that all interactions are via contact interactions between neighboring localized mathematically describable properties, and no influence propagates faster than the speed of light.

By the end of the nineteenth century certain difficulties with the general principles of classical physical theory had been uncovered. One such difficulty was with “black body radiation.” If one analyzes the electromagnetic radiation emitted from a tiny hole in a big hollow heated sphere then it is found that the manner in which the emitted energy is distributed over the various frequencies depends on the temperature of the sphere, but does not depend upon the chemical or physical character of the interior surface of the sphere: the spectral distribution depends neither on whether the interior surface is smooth or rough nor on whether it is metallic or ceramic. This universality feature is predicted by classical theory, but the specific form of the distribution predicted by classical physics differs greatly from what is empirically observed.

Max Planck discovered in 1900 a universal law of black-body radiation that matches the empirical facts. This new law is incompatible with the basic principles of classical physical theory, and involves a new constant of nature, which was identified and measured by Planck, and is called “Planck’s Constant.” By now a very large number of empirical effects have been found that depend upon this constant, and that conflict with the predictions that follow from the basic principles of classical physical theory.

During the twentieth century a theory was devised that accounts in a uniform way both for all of the successful predictions of classical physical theory, and also for the departures of the predictions of classical theory from the empirical facts. This theory is called quantum theory. No confirmed violation of its principles has ever been found.

The Quantum Approach.

The core idea of the quantum approach is the seminal discovery by Werner Heisenberg that the classical model of a physical system can be considered to be an *approximation* to a quantum version of that model. This quantum version is constructed by replacing each numerical quantity of the classical model by an *action*: by an entity that acts on other such entities, and for which the order in which the actions are performed matters. The effect of this replacement is to convert each point-like particle of the classical conceptualization -

such as an electron - to a smeared-out cloudlike structure that evolves in accordance with a quantum mechanical law of motion called the Schroedinger equation. This law, like its classical analog, is local and deterministic: the different elements act by contact with neighbors, and the physical state of any isolated system at any time is determined from its physical state at any earlier time.

This local deterministic quantum law of motion is, in certain ways, incredibly accurate: it correctly fixes *to one part in a hundred million* the values of some measurable properties that classical physics cannot predict.

However, this local deterministic quantum law of motion does not correctly determine human experience. For example, if the state of the universe were to have developed from the big bang solely under the control of the local deterministic Schroedinger equation then the location of the *center* of the moon would be represented in the theory by a structure spread out over a large part of the sky, in direct contradiction to normal human experience.

The smeared-out character of the position of (the center-point of) a macroscopic object, as is a consequence of the famous Heisenberg Uncertainty Principle, combined with the fact that tiny uncertainties at the microscopic level usually get magnified over the course of time, by the Schroedinger equation *acting alone*, to large uncertainties in macroscopic properties.

This contradiction between a mathematical theory that is a direct mathematical generalization of classical physical theory, and that yields many predictions of incomparable accuracy, with the immediate realities of everyday experience is the most basic fact of quantum theory. Its obdurate mathematical certainty allows it to serve as the fulcrum upon which rests a seismic shift in science's concept of science itself, and, in particular, of the relationship between the empirical and theoretical sides of scientific practice. To accommodate the new findings physical science was expanded from a treatment solely of the physically described features of a model to a theory of the complex relationship between the physically and psychologically described aspects of actual scientific practice.

“The Observer” and “The Observed System” in Copenhagen Quantum Theory.

The original formulation of quantum theory is called the Copenhagen interpretation because it was created by the physicists that Niels Bohr had gathered around him at his institute in Copenhagen. A central precept of this approach is that, in any particular application of quantum theory, Nature is to be considered divided into two disjoint parts, “The Observer” and “The Observed System.” The Observer consists of the stream of consciousness of a human agent, together with the brain and body of that person, and also the measuring devices that he (or she) uses to probe The Observed System.

Each Observer is described in a language that allows that human agent to communicate to colleagues two kinds of information: *How he has acted* in order to prepare himself - his mind, his body, and his devices - to receive recognizable and reportable data; and *What the data are* that he thereby acquires. This description is in terms of the conscious experiences of the agent. It is a description of his intentional actions, and of the experiential feedbacks that he subsequently receives.

In actual scientific practice the experimenters are free to choose which experiments they perform: the empirical procedures are determined by the protocols and aims of the experimenters. This element of freedom is emphasized by Bohr in statements such as:

> "The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangement for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude." (Bohr, 1958: 73}

This freedom is achieved in the Copenhagen formulation of quantum theory by placing the empirically/psychologically described Observer outside The Observed System that is being probed, and then subjecting only The Observed System to the rigorously enforced mathematical laws.

The Observed System is, according to both classical theory and quantum theory, describable in terms of mathematical properties assigned to points in space-time. However, the detailed forms of both the laws that govern the evolution in time of this mathematical structure, and also the rules that specify the connection of this mathematical structure to the empirical facts, are very different in these two theories.

I am endeavoring here to avoid mathematical technicalities. But the essential conceptual difference between the two approaches rests squarely on a basic technical difference. This difference can be adequately illustrated by a simple two-dimensional picture.

The Paradigmatic Example.

Consider an experiment in which an experimenter puts a Geiger counter at some location with the intention of finding out whether or not this device will “fire” during some specified time interval. The experiment is designed to give one of two possible answers: ‘Yes’, the counter will fire during the specified interval, or ‘No’, the counter will not fire during this specified interval. This is the paradigmatic quantum measurement process.

This experiment has two alternative mutually exclusive possible responses, ‘Yes’ or ‘No,’ and it can be modeled in a two-dimensional space.

Consider your desk-top, and two distinct points on it called *zero* and *p*. The displacement that would move a point placed on *zero* to the point *p* is called a *vector*. Let it be called *V*. Suppose *V* has unit length in some units, say meters. Consider any two other displacements *V1* and *V2* on the desk top that start from zero, have unit length, and are perpendicular to each other. The displacement *V* can be formed in a unique way by making a (positive or negative) displacement along *V1* followed by a (positive or negative) displacement along *V2*. Let the lengths of these two displacements be called *X1* and *X2*, respectively. The theorem of Pythagoras says that *X1* squared plus *X2* squared is one (unity).

In quantum theory these three vectors, *V*, *V1*, and *V2*, when oriented in certain particular ways, are given specific meanings. The vector *V* represents the state of The Observed System, which has been prepared at some earlier time, and has been evolving in accordance with the Schroedinger equation. The vector *V1* represents the state that this observed system would be known to be in if the outcome of the measurement were 'Yes.' The vector *V2* represents the state that the observed system would be known to be in if the result of the measurement were 'No.' Of course, the directions of the two perpendicular vectors *V1* and *V2* depend upon the exact details of the experiment: on exactly where the experimenters have placed the Geiger counter, and on other details controlled by the experimenters.

The outcome of the probing measurement will be either *V1* (Yes) or *V2* (No). The predicted probability for the outcome to be 'Yes' is *X1* squared and the predicted probability for the outcome to be 'No' is *X2* squared. These two probabilities sum to unity, by virtue of the theorem of Pythagoras. The sudden jump of the state from *V* to either *V1* or *V2* is called a "quantum jump."

The crucial, though trivial, logical point can now be stated: The *orientation* of the set of "basis" vectors, *V1* and *V2,* enters into the dynamics as a *free variable* controlled by the experimental conditions, which are specified by "free choices" made by experimenters. The orientation of the set of basis vectors is thus, from a mathematical standpoint, a variable that can be, and is, specified *independently* of the state *V* of the system being probed.

This entry into the dynamics of the choices made by the experimenters is not surprising. If the experimenters are considered to stand outside, and apart from, the system being observed, as specified by the Copenhagen approach, then it is completely reasonable and natural that the choices made by the experimenters about how to probe The Observed System should be treated as variables that are independent of the variables that specify the physical state of the system they are probing.

Bohr (1958: 92, 100) argued that quantum theory should not be applied to living systems. He also argued that the classical concepts were inadequate for that purpose. So the strict Copenhagen approach is simply to renounce the applicability of contemporary physical theories, both classical and quantum, to neurobiology.

Von Neumann's Formulation.

The great mathematician and logician John von Neumann (1955/1932) rigorized quantum theory to the point of being able to coherently incorporate the devices, the body, and the brain of the observer into the physically described part of the theory, leaving, in the psychologically described part, only the stream of conscious experiences. The part of the physically described system being directly acted upon by the psychologically described "observer" is, according to von Neumann's formulation, *the brain of that observer*. (von Neumann, 1955: 421). Then the quantum jump of the state of the brain of an observer to the 'Yes' basis state becomes the representation, *in the state of that brain*, of the conscious acquisition of the knowledge associated with that answer 'Yes.' The physical features of the brain state actualized by the quantum jump to the state V1 associated with the answer 'Yes' constitute the *neural correlate* of that person's conscious experience of the feedback 'Yes.' This core dynamical structure of (von Neumann) quantum theory means that the basic elements of the problem of the connection between mind and brain are precisely the elements that are connected together by von Neumann's dynamical equations of motion! There is a causally efficacious dynamical process associated with the conscious choice made by the human person. Von Neumann calls it "Process I," and it fixes the orientation of the set of basis vectors – the two vectors V1 and V2 in our simple example.

Von Neumann showed that his formulation of the theory is essentially equivalent, in practice, to the Copenhagen interpretation. But it circumvents the ad hoc separation of the dynamically unified physical world into two differently described parts, and allows the psychological description to be - as is natural - a description of a stream of conscious experiences.

The key conceptual point is that von Neumann's enlargement of the physical system to include the body and brain of the observer *does not disrupt the basic mathematical structure of the theory.* In particular, it does not alter *the critical need to specify the orientation of the set of basis vectors,* in order to tie the theory to ongoing human experiences, and also to complete the determination of the dynamical evolution of the physically described system. In particular, the orientation of the basis vectors associated with a quantum jump *is not determined* by the physical description, *even when that description is extended to include the entire physical world, including the bodies and brains of the human observers.*

That is the central point. In classical physics the incorporation of the entire physical world into the physically described system leads to *the complete determination* of the state of the brain of the observer, and hence to the complete exclusion of the consciousness of the observer from any dynamically necessary role in the determination of the flow of physical events. But in quantum theory there remain these free variables that must be fixed in order to tie the mathematics to human experiences. These variables are, in general, variables that influence our actions. And in the context of scientific practice they are the variables that control the empirical conditions, in accordance with Bohr's dictum. This freedom to choose actions, and hence to specify experimental conditions, persists even when the physically-described system includes the body and brain of the observing agent: an essential dynamical role for this observer/participant's "free choice" of how to act is retained even when the entire body-brain of The Observer is included in the physically described world.

An Altered Perspective.

This leap by von Neumann from the realm of atomic physics to the realm of neuroscience was way ahead of its time: neuroscience was then in a relatively primitive state compared to what it is today; it had a long way to go before mainstream interest turned to the question of the connection between brains and conscious experiences. But seventy years of brain science has brought the empirical side up to the level where the details of the mind-brain relationships are being actively probed, and intricate results are being obtained that can be compared to the predictions of the psycho-physical theory prepared long ago by John von Neumann.

It is evident that a scientific approach to brain dynamics must *in principle* use quantum theory, in order to deal properly with brain processes that depend heavily on chemical and ionic processes. For example, the release of neurotransmitter from a nerve terminal is controlled by the motions of calcium ions, and these ions are small enough so that the deterministic laws of classical physics necessarily fail, and quantum theory must in principle be used to describe the dynamics.

The chief differences at the basic conceptual level between the quantum and classical approaches to consciousness is that the classical principles make no mention of consciousness – and hence specify no well defined theory of consciousness that can be confronted by empirical data - whereas consciousness plays an essential dynamical role in quantum theory. In quantum theory the local-deterministic (i.e., bottom-up) physical process is *causally incomplete*: it fixes, by itself, neither our actions nor our experiences, nor even any statistical prediction about how we will act or what we will experience. The bottom-up process alone is unable to make even statistical predictions, because the statistical predictions depend upon the choice of a set of basis vectors, and the bottom-up local-deterministic quantum process does not fix this choice. This causal gap *not only opens the door* to the possible existence of a dynamically compatible "top-down process" governed by conscious choices, but, at the practical level, *entails the need for* such an extra process, in order to tie the mathematical theory to predictions about human experiences.

This reorganization of the dynamical structure leads to an altered perspective on the entire scientific enterprise. The psychologically described empirical side of scientific practice is elevated from its formerly subservient status - as something that needs to be *deduced* from, or constructed from, the already-dynamically-complete physical side - to the new status of co-equal dynamical partner. Science becomes the endeavor to describe the *two-way interplay* between the psychologically described empirical reality and a physically described mathematical model, rather than an attempt to deduce the existence and the properties of our streams of conscious experiences from a presumed-to-be-dynamically-complete theoretical mechanical model.

Within the von Neumann framework our conscious choices control the orientation of the basis vectors, and hence these choices have, by virtue of this power, the ability to influence our actions. These influences are not illusions. Rather, according to this approach, the experientially described aspects of the theory are able to exercise a certain degree of top-down, consciously controlled, influence.

Pragmatic Neuroscience.

By restricting itself to pragmatic scientific practice the Copenhagen approach was able to restrict the class of "observers" to human beings: "pigs do not do science." Although Bohr often applied his general idea of "the lessons taught by quantum theory" to other domains of science, these applications were by way of analogy, not by way of a strict application of the specific laws of quantum theory.

Von Neumann, in his 1932 book, appeared to follow the Copenhagen idea of focusing on scientific practice. He did not address ontological questions. Those questions must be answered before any claim can be made to have created a satisfactory understanding of the true nature of reality. But they need not be dealt with in order to have a pragmatic scientific theory of the neurodynamics of conscious human brains that relates empirical findings to a mathematical model in a way that allows useful testable predictions to be made, and that is, moreover, philosophically and mathematically, an extension of the methods of atomic physics to the realm of neuropsychology.

Von Neumann's formulation of quantum theory provides the general outline of a pragmatic neurodynamics of the conscious human brain that grows naturally out of contemporary physical theory. All quantum approaches to consciousness start from this von Neumann formulation of quantum theory as the pragmatic base that provides the essential link to the empirical data. But various physicists have proposed augmenting this core structure in different ways. We turn now turn to the descriptions of a number of these proposals.

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